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COMMITTEE ON THE PEACEFUL
USES OF OUTER SPACE

NATIONAL RESEARCH ON SPACE DEBRIS

SAFETY OF NUCLEAR-POWERED SATELLITES

PROBLEMS OF COLLISIONS OF NUCLEAR-POWER SOURCES WITH SPACE DEBRIS

Note by the Secretariat

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INTRODUCTION

1. In its resolution 48/39, paragraph 27, of 10 December 1993, the General Assembly considered it essential that Member States pay more attention to the problem of collisions of space objects, including nuclear power sources, with space debris, and other aspects of space debris, and called for the continuation of national research on that question, for the development of improved technology for the monitoring of space debris and for the compilation and dissemination of data on space debris. To the extent possible, the Assembly noted, information thereon should be provided to the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space.

2. The General Assembly, in paragraph 14 of the same resolution, invited Member States to report to the Secretary-General on a regular basis with regard to national and international research concerning the safety of nuclear-powered satellites.

3. The Committee on the Peaceful Uses of Outer Space, in the report of its thirty-seventh session (A/49/20, para. 77) agreed that Member States and relevant organizations should be encouraged to provide information on practices that they had adopted and that had proved effective in minimizing the creation of space debris.

4. The Secretary-General addressed a note verbale dated 13 July 1994 to all Member States, inviting them to communicate to the Secretariat, by 30 November 1994, the information requested above so that the Secretariat could prepare a report containing this information for submission to the Subcommittee at its thirty-second session.

5. The present document was prepared by the Secretariat on the basis of information received from Member States and international organizations as of 30 November 1994. Information received subsequent to this date will be included in addenda to the present document.

REPLIES RECEIVED FROM MEMBFR STATES

Belgium

[Original: French]

The Government of Belgium reports that at present no research is being carried out in the area of space debris.

Canada

[Original: English]

Canadian space experiments

Canada has been actively involved in the characterization of the low Earth orbit (LEO) orbital debris environment through ground-based analysis and test, and in-orbit experiments. Those have included the Long Duration Exposure Facility (LDEF), and two Shuttle experiments: Materials Exposure in Low Earth Orbit (MELEO) and Advance Composite Materials Exposure Experiment (ACOMEX). Although these experiments were designed to measure other effects of the environment, they have also provided an opportunity to contribute to the understanding of the orbital debris environment. Specific details of each are provided below.

Materials Exposure in Low Earth Orbit

MELEO was an active experiment flown on Shuttle mission STS-52 in October 1992. The experiment was primarily designed to measure the effect of the environment on material specimens (313 in total) which were mounted on the Canadarm (the Canadian robotic arm on the United States Shuttle) and exposed in the "ram" direction during the mission for a total of approximately 30 hours. The experiment also included two active quartz crystal microbalances which were designed to operate in reverse fashion to measure the atomic oxygen fluence during exposure. The experiment was developed by a number of co-investigators, several of whom included materials designed to capture small orbital debris particles and micrometeorites.

During the mission, a solid rocket motor was used to raise a satellite payload to a high orbit after deployment from the Shuttle. It was this event that provided the majority of data on orbital debris during the mission. Although the material specimens were protected during the firing itself, many of the specimens which were returned to Earth for evaluation had been impacted by many small particles. The estimated particle size was consistent with the expected effluent from the solid rocket although the duration of persistence of the debris cloud was not expected. As a result, this experiment provided data on the orbital debris caused by the burning of a solid rocket motor.

Advance Composite Materials Exposure Experiment

ACOMEX was also a Shuttle-based experiment flown on STS-41G in October 1984. The purpose of this experiment was to gather data on the degradation of composite materials in low Earth orbit. The experiment consisted of a number of material specimens mounted on the Canadarm which was positioned in the "ram" direction for approximately 40 hours during the mission. This experiment was not designed to measure orbital debris but examination of the specimens returned to Earth after the mission provided some observations which were identified as likely a result of impacts from space. Although no detailed data was obtained, this experiment did contribute to the design of the MELEO experiment noted above.

Long Duration Exposure Facility

One of the experiments aboard LDEF was provided by Canadian Investigators from the University of Toronto. Much has been published to date on the results from the LDEF spacecraft which include the results obtained from this Canadian experiment. After return to Earth this experiment was thoroughly examined to identify impact sites. Over 70 impact sites were clearly identified. In addition, the data from the entire spacecraft as reported through the Orbital Debris Investigation Group was analysed and presented in the form of an Engineering Monogram that could be used for the design of spacecraft. Furthermore, ground testing has been used to correlate the size and type of damage experienced by the specimens to probable particle sizes and velocities.

A number of papers have been published as a result of this work.

Practices adopted in minimizing the creation of space debris

In order to minimize the creation of space debris, the RADARSAT programme undertook two specific preventative measures.

The first preventative measure consisted of establishing a system level requirement that any solid debris resulting from the operation of a restraint/release mechanism be contained. That is, all contractors were required to design a system such that no debris would be released by the spacecraft during deployment.

The second preventative measure consisted of protecting the RADARSAT spacecraft from the existing space debris environment. This measure was undertaken in order to ensure, to the best possible extent, that the RADARSAT spacecraft does not prematurely become space debris as a result of space debris impact.

The second preventative measure consisted of defining the space debris environment to be encountered by RADARSAT using the NASA EnviroNET database. Individual spacecraft components were then examined to determine their vulnerability to this predicted environment. This vulnerability assessment included using hypervelocity impact equations as well as actually subjecting spacecraft hardware to hypervelocity impact tests at the NASA Johnson Space Centre. When required, shielding was added to the spacecraft in order to bring the survivability of the spacecraft to an acceptable level. The shielding included adding Nextel (a 3-M ceramic fibre cloth) to thermal blankets, adding bumpers in front of exposed hydrazine lines and wire bundles, and thickening some component boxes in order to protect their enclosed circuits.

Hungary

[Original: English]

Hungary is well aware that the existence of space debris is a common and very serious problem.

However, real steps towards the solution of this dangerous problem can only be taken by States already substantially engaged in space research, and international organizations and bodies which are working in different fields of space activities. Organizations such as the Committee on Space Research and the International Academy of Astronautics may considerably help the endeavours of the Committee on the Peaceful Uses of Outer Space.

Hungary has attempted to conduct theoretical investigations (e.g. mathematical modelling) of collision cases. We are informed however, that a number of Member States with a much better background than Hungary have applied for conducting these investigations.

Unfortunately, Hungary - as is the case with some other small Member States - is not in a position to start a programme in this area. The only means of contributing is through negotiations, meetings and other forums, where the statements of each country can help in solving this growing problem.

It would be most beneficial, however, if the exchange of information on this subject were promoted, enabling nations such as Hungary to participate in the ongoing research.

Japan

[Original: English]

Introduction

This paper describes the current and planned efforts in the space debris field in Japan, placing emphasis on the activities of the Japan Society for Aeronautical and Space Sciences (JSASS) and the National Space Development Agency of Japan (NASDA). It covers activities for space debris environment measurement, mitigation, and protection and shielding. Some representative activities of individual researchers are also briefly introduced.

Although the earliest warning of the potential hazard of the space debris problem had been made by a Japanese researcher,[1] neither systematic nor organized activities were conducted until 1990 in Japan. Stimulated by the report of the United States Inter-Agency Space Debris Working Group and the advocates for international cooperation from the United States, the importance and urgency of this problem have been recognized and recently related research and development activities have become high priority issues.

As a forerunner of recent activities, JSASS organized the Space Debris Study Group in September 1990 and, after a two-year extensive study issued the final report in March 1993.[2] As a follow-up on some of the recommendations in that report, two new JSASS study groups: the Study Group on Space Debris Prevention Design Standards and the Study Group on Space Debris and Micrometeoroid Impact Detection began their activities in July 1993.

Recognizing the potential hazard of space debris to its future space development activities, NASDA, as the implementing organization of Japan's space development activities, formed an in-house Space Debris Working Group in August 1993.

Some of the results obtained by the three groups mentioned above and the representative activities of individual researchers are introduced and evaluated in this paper.

Measurement of space debris environment

Optical and radar observation

At present, there is no dedicated system for space debris observation in Japan. However, three independent observation activities utilizing optical telescopes and radar systems constructed originally for other purposes should be mentioned.

The first is the Communication Research Laboratory's (CRL) optical observation system (located 35.42° N, 139.29° E), which comprises a 1.5 m telescope, a liquid nitrogen cooled charge-coupled device (CCD) camera and an image processing computer. It was originally constructed as the ground station of an optical communications experiment in space. The system is used to observe objects in the vicinity of the geostationary earth orbit. Until now tracking objects was limited to operational geostationary satellites, but with the newly developed image processing technique of CRL and its theoretical observation capability

of 20 cm objects in the geostationary Earth orbit, some contribution to debris environment measurement in this important orbit is expected.

Secondly, NASDA is currently conducting a study which considers the need for ground-based and on-orbit observation systems for space debris. As a part of the study of ground-based observation, NASDA requested the National Astronomical Observatory (NAO) to conduct preliminary studies on the optical measurement of satellites. In October 1992, a trial was made to observe the spent geostationary meteorological satellite GMS-4 (Himawari-4) using a telescope with a 60 cm mirror in Kagoshima Space Center (KSC) of the Institute of Space and Astronautical Sciences (31.13° N, 131.04° E). The telescope was specially equipped by a CCD camera for this study. The principal parameters of the equipment are shown in table 1.

Table 1. Principal parameters of the equipment

Parameter	Value
Telescope	
Aperture	60 cm
Timing error	1 s
Exposure time	60 s, 100 s
Field of view	0.19 x 0.14°, 14° x 4.2°
CCD Camera	
Type	Hamamatsu-Photonics C3140, Water cooled CCD
Chip size	512 x 492
Operational temperature	233 K

For determining the brightness class of stars and objects, IRAF software for image processing developed by the National Optical Astronomy Observatories (NOAO) of the United States of America and the Guide Star Catalogue (GSC) prepared for the Hubble Space Telescope project were used.[3]

Based on the results of this study, a proposal was made to build a CCD telescope fully dedicated to the observation of rapidly moving celestial objects. It should be a Schmidt camera, with an aperture greater than 50 cm and focus length of 1-1.2 m, equipped with a CCD (1.5 cm square) cooled by liquid nitrogen with 1,000 x 1,000 pixels. Furthermore satellites were observed in 1993 and 1994, using the Schmidt telescopes of the KSC and the Kiso Observatory of Tokyo University.

The third observation system is the Middle and Upper Atmosphere (MU) radar system (34.8° N, 136.11° E). The system is a monostatic pulse Doppler radar operating at 46.5 MHz with an active phased array antenna of 103 m in diameter and a peak output power of 1 MW. As described in an earlier review paper[4] it has unique characteristics for the acquisition of data on debris shape and rotational motion. By continuing observation of LEO objects, a study on the improvement of shape and motion estimation algorithms is now being conducted.

Feasibility studies on the Bistatic Radar and the Laser Radar Systems

A new concept in space debris observation systems, which is composed of a Nd:YAG laser, a light-beam expander, a telescope, a CCD area sensor, a photo multiplier and a CPU, as shown in figure 1 and table 2, has been proposed in a study.[5] It is expected to have the observation capability to detect a particle of 1 mm in diameter at a distance of 1 km, and can be used as an on-board space debris observation system to locate small debris undetectable from the ground for collision avoidance manoeuvres. A laboratory model has been manufactured and its basic performance is being tested.

Table 2. Specifications of laser radar

Parameter	Value
F-number	F2
View angle	90 degrees (±45 degrees)
Wavelength	532 nm (Nd:YAG 2nd harmonics)
Imaging area	14.4 x 10.8 mm (18 mm diameter)
Image spot size	<10 μm
Distortion	<10%
Focal length	9.2 mm (at D-line)
Transmittance	>70%

A study on bistatic radar observation technology, from the viewpoint of the utilization of worldwide existing facilities of the ground has also been conducted.[6] Using 10 m and 20 m antennas, KSC as a transmission station and the 64 m at the Usuda Deep Space Center as a reception station, the applicability of this technique in the observation experiment of Yokoh, a scientific satellite in a circular orbit at 1,600 km altitude, was successfully demonstrated. It is emphasized that by means of modern communication technology this kind of system could be sophisticated enough to have the capability to observe small objects of 19 mm in diameter at 500 km altitude.

Dust-capturing experiment in JFD programme

Other efforts have been directed toward the planning of on-orbit particle collection equipment to be mounted on the Japanese Experimental Module Flight Demonstration (JFD). JFD is proposed for testing the Japanese manipulator system on board the Space Shuttle for the purpose of verifying the system for the Japanese module (JEM) of the International Space Station. Utilizing this opportunity, the Parts and Materials Laboratory (PML) of NASDA is planning on carrying out the Experiment of Space Environment with Materials (ESEM). The ESEM system consists of dust or space debris collectors (DC) and material sample holders (MSH) for evaluation of the atomic oxygen effect in space. They are to be mounted on the top of the JFD experiment apparatus in the Shuttle payload bay, and are to be exposed to the Shuttle flight direction for 40 hours. The configuration of the JFD experiment, a candidate for the dust collector and the expected collision number are shown in figures 2 and 3 and table 3.[7] The mission is scheduled for April 1997, and is expected to provide new environmental data on cosmic dust and space debris.

Table 3. Expected number of dust and space debris impact events

Dust diameter (μm) (Dust mass (gram))	Dust counts	
	JFD	JEM (1 year)
1 ~ 5(10^{-11} ~ 10^{-10})	28.60	16 252.45
5 ~ 10(10^{-9} ~ 10^{-8})	0.48	256.80
10 ~ 50(10^{-7} ~ 10^{-6})	0.15	65.42
50 ~ 100(10^{-6} ~ 10^{-5})	-	1.86
100 ~ 500(10^{-5} ~ 10^{-3})	-	0.40
500 ~ 1000(10^{-1} ~ 10^{-2})	-	0.01

Post-flight analysis of the Space Flyer Unit

Japan's retrievable free flyer, the Space Flyer Unit (SFU), is scheduled for its first six-month mission, in a circular orbit with a mean operational altitude of 482±20 km and an inclination of 28.5 degrees. It will be placed in orbit by the third launch of the H-II rocket in February, 1995 (figure 4). After its retrieval by a Shuttle orbiter, it will be the first space component safely returned to Earth for Japan. It is crucial to take this opportunity and operate a scientifically efficient post-flight analysis (PFA) of the spacecraft, which will be the world's third PFA activity of an entire spacecraft body and will also provide a large amount of data on small space debris and micrometeoroid distribution. Consequently in 1993, JSASS organized a Study Group on Space Debris and Micrometeoroid Impact Detection to discuss the methodology and procedures of PFA of retrieved spacecraft. Based on one year of intensive study the Group has made a proposal for the SFU/PFA, which includes the morphology measurement of craters to the SFU development consortium.

The total exposed area of the SFU is approximately 146 m^2. Among the suitable surfaces for PFA are four main, large areas:

(a) Payload Unit Multi-Layer Insulation (MLI): a 4.46 m diameter octagonal structure 1.40 m high, combining six segments at 50° and two segments at 30°;

(b) Exposed Facility Flyer Unit (EFFU): a box-like structure, the top surface of which is covered with silver-coated Teflon (a 1.48 m x 1.48 m top surface radiator and four-sided aluminized Kapton MLI 1.05 m high);

(c) Two solar array panels (9.7 m x 2.4 m each);

(d) Two-dimensional high voltage solar array (2D/HV): a triangular sail 3.84 m high with a 3.62 m base line in the full open configuration. Both sides of the solar array and the 2D/HV sail can be examined doubling the exposed area under investigation.

Recently, trial estimates have been made[8] of the expected impacts by micrometeoroids heavier than 10^{-9} g and space debris larger than 10 μm in diameter using ESABASE. The results are shown in table 4. It is expected that a considerable amount of information will be obtained by comparison with LDEF, Eureka and HTS solar array PFA data. Japan proposed the construction of a comprehensive database of

hypervelocity impacts in space through international cooperation at the 11th Inter-Agency Debris Coordination (IADC) committee meeting held in May 1991 at Tsukuba, Japan.

Table 4. Expected number of dust and space debris impacts

Major surfaces	Meteoroid (>10^{-9} g)	Space debris (>10 μm)
Solar panels (Sun face)	4 321 ~ 3 920	4 249 ~ 3 824
Solar panels (anti-Sun face)	3 862 ~ 3 551	4 036 ~ 3 611
EFFU Sides	374 ~ 334	436 ~ 382
Payload multilayer insulation	1 106 ~ 1 015	1 324 ~ 1 200

Development tests for the Japan Experiment Module

As the implementing organization of the international space station programme in Japan, NASDA is now developing the Japan Experiment Module (JEM). In designing its bumper structure, a two-stage hydrogen light gas gun was developed (figure 5). Using it, hypervelocity impact (HVI) tests of more than a 100 cases have been conducted in various configurations.[3]

The main purposes of the HVI tests were:

(a) To examine whether hoop stress may have influence on impact damage;

(b) To investigate the possibility of unzipping phenomena occurring under the condition of 1 atmosphere internal pressure;

(c) To verify the equivalent or better shielding performance of the isogrid skin compared to that of the waffle skin, because the former stiffening configuration is the design baseline;

(d) To examine the failure tolerant performance of the isogrid skin;

(e) To study the effect on impact damage of MLI placing between the bumper plate and the pressure wall.

Detailed analysis of the test results are still being carried out, but the following facts have been revealed by a quick review of the data:

(a) Initial tensile stress hardly affects the penetration hole diameter;

(b) Unzipping failure was not observed under the uniaxial tensile stress corresponding to 1 atmosphere internal pressure but was observed under the condition stressed by three times (figure 6);

(c) Impact damage could propagate beyond the rib stiffener (figure 7), but it showed resistance to some extent;

(d) By installing MLI between the bumper and the wall, the penetration hole becomes smaller but the crack length becomes larger.

Basic research activities in the National Aerospace Laboratory

The National Aerospace Laboratory (NAL) is concentrating its efforts on the basic research of HVI phenomena. As described in the previous review paper,[4] the Laboratory has been conducting HVI experiments in various velocity ranges (~2 km/s-, ~4 km/s and ~7 km/s) in cooperation with Kyoto University, Tohoku University and ISAS. Utilizing the data acquired, it was demonstrated that the Lagrangian approach combined with interactive rezoning is applicable and effective as an analysis and design tool in this kind of problem. The focus then moved to the optimization of the material model in each velocity range. A lot of numerical simulation has been carried out with various combinations of the strength model, the equation of state, maximum hydrostatic tensile stress and ultimate strain in order to determine the best combination to simulate their experimental data.[9] As for the case of the 2024-T3 aluminium target and the Polycarbonate or high density polyethylene projectile, some of the simulation and experimental results show excellent agreement with each other in figures 8 and 9.

Besides the basic research mentioned above, NAL is developing the inhibited shaped charge launching system with Mitsubishi Heavy Industries, Ltd. and is also planning a series of explosion experiments for modelling the break up of the rocket upper stage.

Conclusion

The current and planned activities in the space debris field in Japan have been reviewed. As a result of the continuing efforts of the JSASS Space Debris Study Group since 1990, Japanese space-related organizations have been aware that the space debris hazard is no longer an abstract problem, but rather a real and serious threat to manned and unmanned activities in space. The Science and Technology Agency (STA) is now making an intensive effort to establish a National Policy on the space debris problem. NASDA also formed an in-house Working Group on 5 August 1993 to study the space debris problem, and to establish the NASDA policy and debris mitigation and protection design standard. The JSASS Study Group will continue its activities focusing on the scientific and technical aspects of the space debris issue.

This paper has been written to introduce space debris related activities in Japan, however, space debris is intrinsically a global problem. It must be well understood that efficient and cost-effective solutions should be found through cooperative discussions among all space-faring nations and organizations.

Notes

[1]M. Nagatomo, H. Matsuo and K. Uesugi, "Some considerations of the near Earth in future", Proceedings, 9th International Symposium on Space Technology and Science (Tokyo, 1971), p. 257.

[2]Japan Society for Aeronautical and Space Sciences, "Final report of the Space Debris Study Group" (1992).

[3]A. Takano, "Recent activities of space debris related works in NASDA", 19th International Symposium on Space Technology and Science (1994).

[4]S. Toda and T. Yasaka, "Space debris studies in Japan", Adv. Space Res., vol. 13, No. 8 (1993), pp. 289-298.

[5]T. Yokota and others, "Consideration of a laser radar system for space debris measurement", 19th International Symposium on Space Technology and Science (1994).

[6]T. Takano, M. Yajima and K. Tsuchikawa, "Space debris monitoring by networking large antennas," 19th International Symposium on Space Technology and Science (1994).

[7]T. Ono and T. Kurosaki, "The experiment of space environment with materials on JFD project", 19th International Symposium on Space Technology and Science (1994).

[8]H. Yano and S. Kibe, "Post flight analysis of retrieved spacecraft", 19th International Symposium on Space Technology and Science (1994).

[9]M. Katayama, S. Kibe and S. Toda, "A numerical method and its validation for space debris protection system", 19th International Symposium on Space Technology and Science (1994).

Figures

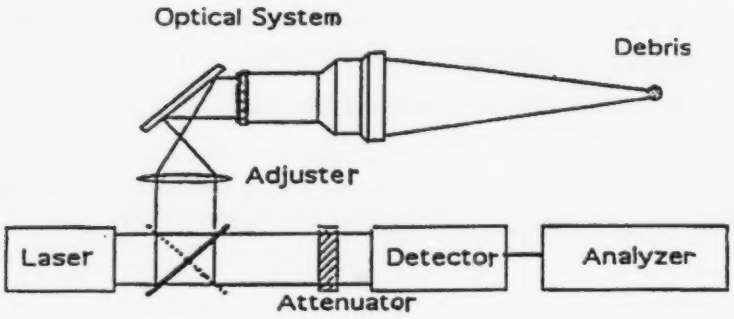

Figure 1: Laser Radar System.

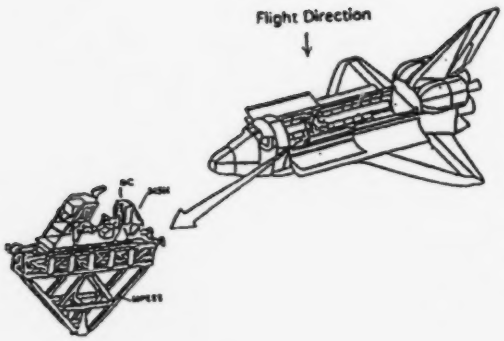

Figure 2: JFD Configuration.

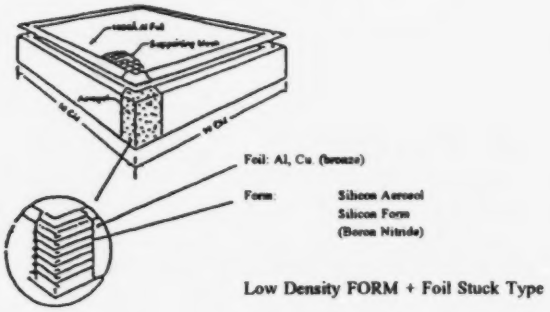

Figure 3: Dust Collector.

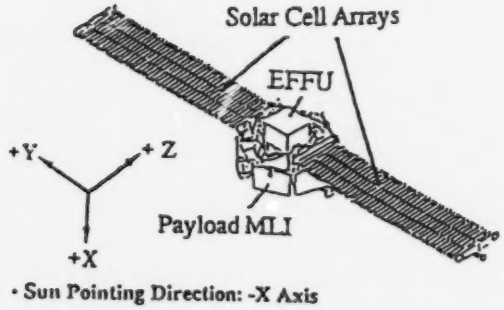

Figure 4: SFU Configuration.

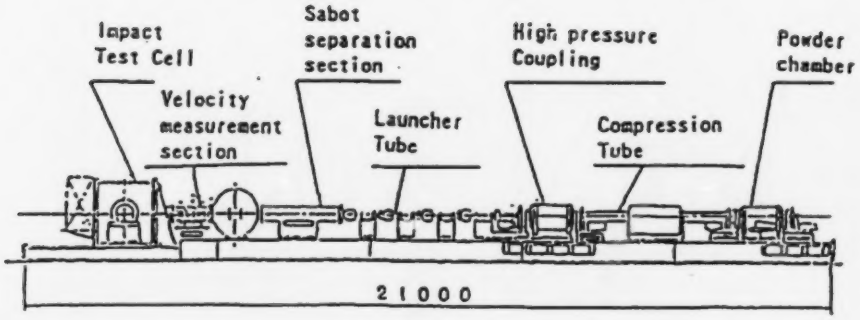

Figure 5: NASDA's Two Stage Hydrogen Gas Gun.

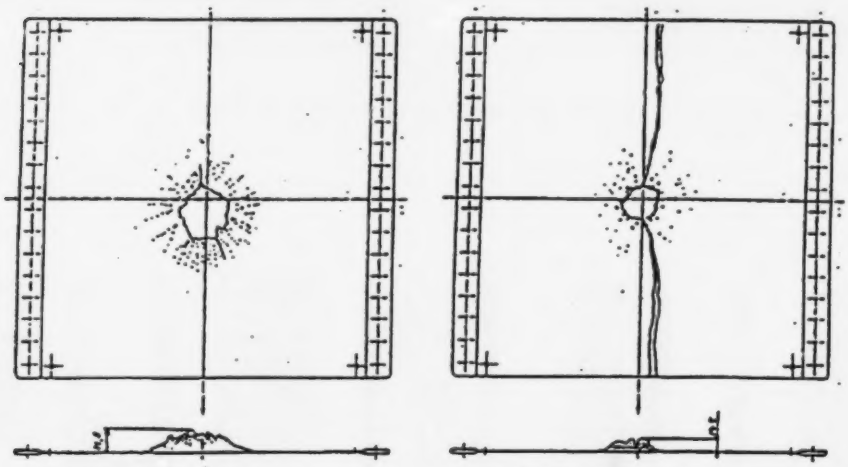

Figure 6: Unzipping Test Results (t = 0.8 mm, σ = 7 kgmm^{-2}, 21 kgmm^{-2}).

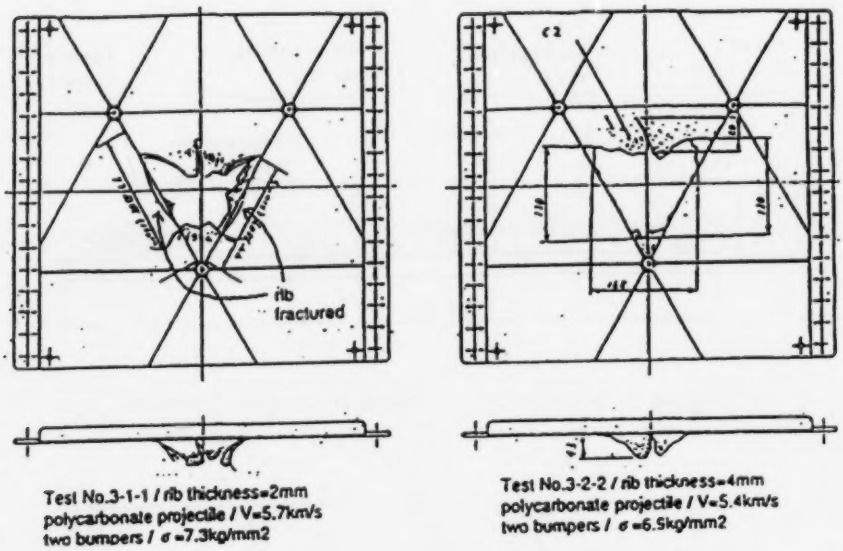

Figure 7: Crack Propagation in an Isogrid Panel.

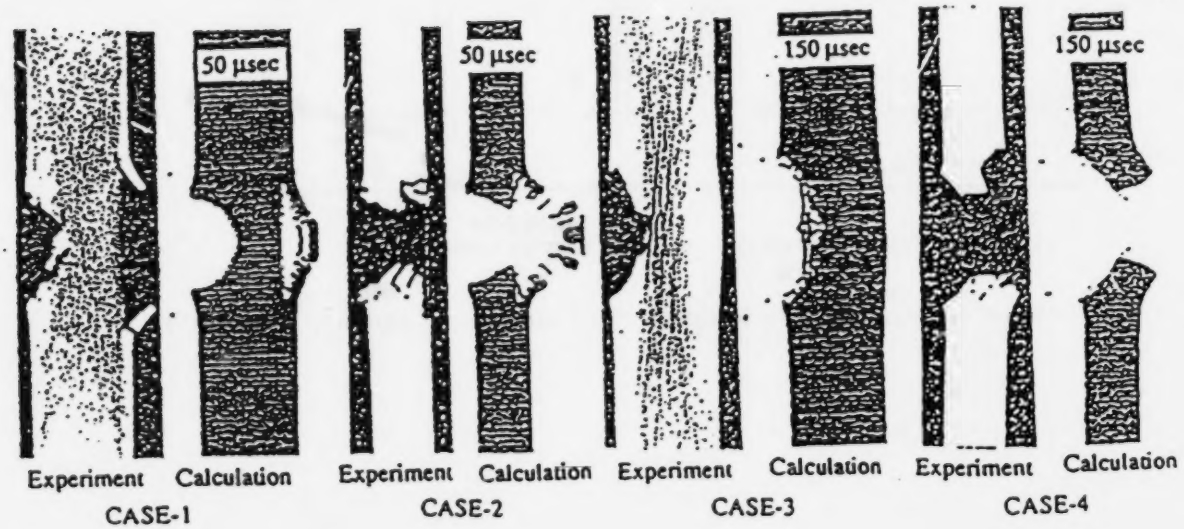

Figure 8: Comparison of the Final Target Profiles between the Experiments and Calculations

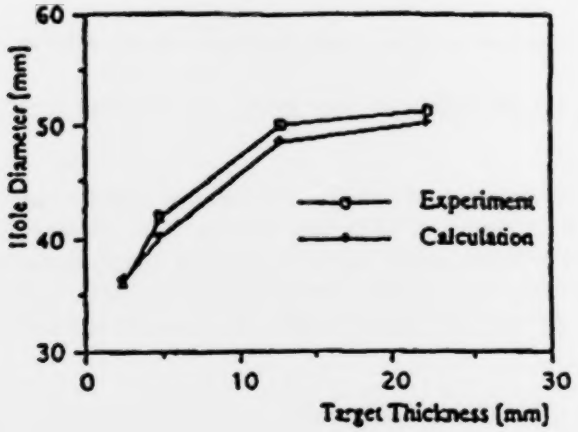

Figure 9: Target Thickness vs. Perforation Diameter.

Malta

[Original: English]

As Malta has no space activity or national or international research concerning the safety of nuclear-powered satellites, it has no report to present.

Poland

[Original: English]

Poland will submit its national report on space debris research to the forthcoming session of the Committee on the Peaceful Uses of Outer Space.

Sri Lanka

[Original: English]

Sri Lanka states that at present it is not conducting any research relating to space debris.

United Kingdom of Great Britain and Northern Ireland

[Original: English]

In March 1994 and September 1994, the British National Space Centre joined the national space agencies of Germany (DARA), France (CNES), and Italy (ASI) in discussions with the European Space Agency to identify national facilities which could be used for space debris research, and to harmonize research activities for a common policy on space debris mitigation. Both meetings were very successful and initiatives proposed at the meeting such as the collaborative use of national facilities are being actively followed.

The second United Kingdom Orbital Debris Industry/Academia Coordination Group Meeting was held at the University of Kent in Canterbury in May 1994. Representatives from the United Kingdom Government, industry and universities met to build on the success of the first meeting held in 1993. A number of joint studies were carried out as a result of the first meeting focusing on the short- and long-term risk to operational satellites. Following this meeting it was agreed that attention should be given to the derivation of debris environment characteristics from the analysis of spacecraft surfaces retrieved from orbit. The next meeting is planned for early 1995.

A three-day residential course on space debris was held at the University of Kent in September 1994. The course was sponsored by Century Dynamics (UK), Defence Research Agency (UK), European Space Agency, Kaman Sciences Corporation (United States of America), Matra Marconi (France), Space Guard (Australia), University of Braunschweig (Germany), University of Kent and University of Utrecht (the Netherlands). Experts gave presentations on a range of debris disciplines to representatives from the industrial, academic and governmental sectors of Europe and the United States of America. It is expected that following the success of the course, further events will be run at intervals of from two to three years.

A number of technical papers have been produced by United Kingdom researchers during 1994:

The problem of predicting the long-term growth of the satellite and debris population in Low Earth Orbit (LEO) was addressed by McInnes.[1] The study concluded that with current levels of debris deposition into orbit, catastrophic growth of collision fragments should not occur for at least 10 years. However if the deposition rate grows, the cascading phenomenon may occur as soon as 2040. Attention should also be

focused on where future debris is deposited into orbit as this has a major influence on the debris population growth.

UNISPACE,[2] the Unit for Space Sciences at the University of Kent leads the European community in the analysis of space surfaces returned from orbit.[3] Recent flight opportunities which have provided UNISPACE with the opportunity of validating environment models against actual impact data were the European Retrievable Carrier (EURECA) and Hubble Space Telescope (HST) servicing mission.[4] In both cases retrieved surfaces such as solar arrays were analysed for evidence of impact phenomena. These data were supplemented by dedicated flight experiments[5] on board the EURECA platform. The results provide a valuable opportunity of comparing the encountered particulate environment in orbit from two epochs,[6] i.e. when the Long Duration Exposure Facility (LDEF) (prior to 1990) and EURECA/HST[7] (post 1990) satellites were in orbit. These epochs are separated by a peak in the solar activity cycle. At this time the atmosphere heats up, expands and the dynamic processes affecting debris orbital lifetime can be investigated.[8] In order to relate the crater morphology to impactor characteristics[9] UNISPACE must carry out extensive simulation[10] both in the laboratory[11] and using hydrodynamic[12] computer codes. Major advances have been made by UNISPACE in determining impactor population characteristics from retrieved surface analysis[13] and predicting impact damage under a variety of encounter conditions.

The University of Southampton continues to develop its expertise in short-term risk modelling in conjunction with the Defence Research Agency. It has applied its modelling approach to investigate the effects of satellite breakup and debris impingement on a number of satellite systems. They first considered the possibility of a cascade fragmentation following the breakup of one of a family of constellation satellites.[14] The study concluded that the short-term collision risk following a satellite breakup in a modest-sized constellation was low but may increase to significant levels if a large number of satellites were included in a constellation. The second study considered the breakup of a launch vehicle upper stage in the proximity of a remote sensing platform such as ENVISAT.[15] The study concluded that a collision hazard many times larger than that due to the background debris population would be experienced if such a breakup occurred close to a remote sensing platform, leading to the possibility that the payload itself could be damaged.

Queen Mary College and Westfield College, University of London, have begun to apply their extensive knowledge in collision dynamics derived from rarefied gas-flow modelling to the field of orbital debris. The study[16] revisited the problem of characterizing collision frequency in support of planned long-term debris population evolution studies. The conclusion is that source fragment distribution functions will dictate whether conditions permit cascading to occur, and that the classical approach used to represent collision frequency may overestimate the required critical spatial density of debris needed to sustain cascading.

The Royal Greenwich Observatory continues to improve understanding of the capability and limitations of optical telescopes for detecting and tracking debris objects in orbit. The Observatory produced two papers this year, both focusing on the performance of a generic optical detection system and its ability to detect the breakup event and track the resulting fragments following satellite fragmentation. The first study[17] carried out jointly with the Defence Research Agency considered the breakup of a satellite on the geostationary ring. A second paper[18] investigating a breakup in highly eccentric orbit was carried out jointly with the Defence Research Agency and the University of Kent. In both cases fragment detectability was limited by its dimensions, reflectivity and the actual trajectory of the fragment relative to the observing station.

The Defence Research Agency (DRA) continues to be involved in a broad range of activities relating to orbital debris. In addition to collaboration with the University of Kent, University of Southampton and Royal Greenwich Observatory on studies, it acts as a national technical focus advising groups new to the field. DRA continues to build on its experience of predicting orbital lifetime and re-entry of debris objects.

More recently it has considered the phenomenon of aerodynamic heating in an attempt to predict the re-entry state[19] of debris as it returns to the Earth's atmosphere. DRA has also developed new techniques for characterizing the risk to a satellite of an object fragmenting in a neighbouring orbit.[20] DRA is also developing a system of characterizing the potential pollutive impact of a mission on the space environment and using this to assess the cost benefit tradeoff of particular mission designs.[21]

Notes

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[16]J.P.W. Stark, "Direct Monte-Carlo simulation of orbital debris", paper presented at 19th International Symposium on Rarefied Gas Dynamics (Oxford, 1994).

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REPLIES RECEIVED FROM INTERGOVERNMENTAL AND INTERNATIONAL ORGANIZATIONS

International Atomic Energy Agency

[Original: English]

The safety principles on nuclear power sources in space established by the Committee on the Peaceful Uses of Outer Space are based on recommendations from the International Commission on Radiological Protection (ICRP). The most recent ICRP recommendations have been translated by a joint secretariat of FAO/IAEA/ILO/NEA (OECD)/PAHO/WHO into the new International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS). The Board of Governors of IAEA approved the Standards at its 847th meeting on 12 September 1994. For the Pan American Health Organization (PAHO), the XXIVth Pan American Sanitary Conference endorsed the Standards on 28 September 1994, following a recommendation from the 113th meeting of the PAHO Executive Committee. The Director-General of the Food and Agriculture Organization of the United Nations (FAO) confirmed its technical endorsement of the Standards on 14 November 1994. The Governing Body of the International Labour Organisation (ILO) approved the Standards on 17 November 1994.

An interim publication of BSS in English is expected to be issued before the end of 1994. It is expected that the final multilanguage publication will be issued in 1995, after the adoption of BSS by the other organizations. Although these Standards were not developed with the specific problems of sources in outer space in mind, they are basically applicable to any type of radiation sources and, therefore, their general use for those sources should be considered.

Furthermore, IAEA has, in its Safety Series, issued more than 100 documents (standards and guidance) on the safety of reactors in land-based nuclear power plants and also on research reactors. Many requirements and recommendations in these documents may be applicable to the safety of nuclear power sources in outer space. These standards and guides are reviewed continuously. As an example, IAEA has prepared a Safety Series document on Emergency Planning and Preparedness for Nuclear Powered Satellite Reentry, which will be published in 1995. The preparation of this document was initiated by inquiries received by the Agency during the period in 1988 when the future of Cosmos 1900 was unclear. The purpose of this document is to provide a general and comprehensive overview of the management of incidents or emergencies that may be created when nuclear power sources employed in space systems accidentally reenter the Earth's atmosphere and impact on its surface.

In addition to the establishment of safety standards and guides, the Agency carries out an important programme of activities on radiation safety in the areas of education and training, research and development, cooperation and assistance, information exchange and services. These activities, which are highlighted in the Agency's Programme and Budget for 1995/96 (Programmes H and I) are generally usable for programmes on the safety of radiation sources in outer space.

Committee on Space Research

[Original: English]

The International Academy of Astronautics (IAA) position paper on orbital debris (see annex to the present document) is the product of an ad hoc expert group of the IAA Committee on Safety, Rescue and Quality, a group which includes a number of experts from the Committee on Space Research (COSPAR). Therefore, the report fully reflects the point of view of COSPAR on these matters as elaborated by its Panel on Potentially Environmentally Detrimental Activities in Space. This position paper has been approved by

the Board of Trustees of IAA at its session of 19 October 1993 at Graz, Austria, and the conclusions remain fully valid for the present.

International Telecommunications Satellite Organization

[Original: English]

The International Telecommunications Satellite Organization (INTELSAT) has adopted the following practices to minimize the creation of space debris:

(a) At the end of their operational lifetimes, INTELSAT will boost its communication satellites into an orbit at least 150 km above the geostationary arc. The intended increase in orbit will be 300 km for the INTELSAT VI and all later series satellites;

(b) INTELSAT will discourage manufacturers of its spacecraft from using designs that jettison spacecraft parts, especially near geostationary orbit. For example, solid rocket motor casings and solar-array cable wraps will stay attached to the spacecraft.

Annex

IAA POSITION PAPER ON ORBITAL DEBRIS*

1. INTRODUCTION

Since 1957, mankind has performed more than 3,400 space launches into Earth orbit. The large number of spacecraft, rocket bodies, and other hardware associated with these missions subsequently encounter one of three fates: (1) reentry into the Earth's atmosphere, (2) escape from Earth orbit into deep space, or (3) remaining in Earth orbit (Fig. 1).

After nearly 35 years of international space operations, almost 22,000 objects have been officially cataloged with approximately one-third of them still in orbit about the Earth (Fig. 2). "Cataloged" objects are considered to be objects larger than 10 - 50 cm in diameter for LEO and 1 m in diameter in higher orbits, which are sensed and maintained in a database by the United States Space Command's Space Surveillance Network (SSN). (Appendix B describes space surveillance facilities in more detail.)

The purpose of this position paper is to review the growth of the population of man-made objects in Earth orbit, with emphasis on orbital debris and on the hazard presented to current and future space operations, and to assess preventive measures for debris reduction.

Orbital debris is herein defined as any man-made Earth-orbiting object which is non-functional with no reasonable expectation of assuming or resuming its intended function or any other function for which it is or can be expected to be authorized, including fragments and parts thereof. Orbital debris includes non-operational spacecraft, spent rocket bodies, material released during planned space operations, and fragments generated by satellite and upper stage breakup due to explosions and collisions. (See **Categories of Orbital Debris.**) This derelict hardware is strewn across a wide range of altitudes, but is clustered around regions where space activity has been the greatest: LEO and GEO. A lesser amount of debris currently resides in HEO. Orbital debris continually passes through space shared with functioning fragile and expensive spacecraft, manned and unmanned, performing vital navigation, communications, remote sensing, surveillance and scientific missions. Orbital debris may present a variety of problems to the spacefaring community, from the possibly catastrophic collision hazard to the corruption of astronomical observations and intermittent interruption of RF paths.

The original particulate design environment for spacecraft considered meteoroids

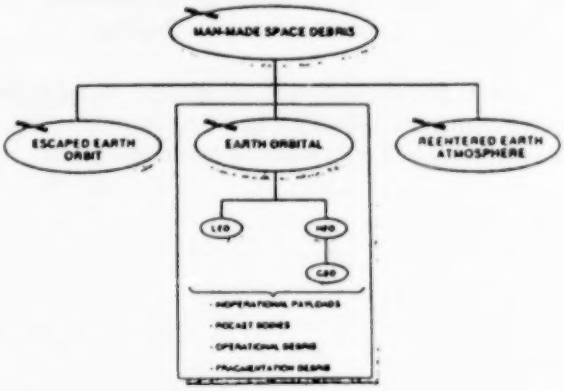

Figure 1. Debris categorization: Man-made space debris may escape Earth orbit, reenter Earth's atmosphere, or remain in Earth orbit. This position paper is concerned only with Earth orbital debris. LEO = low Earth orbit up to 225 min; GEO = geostationary orbit, 35787 km; HEO = high Earth orbit above 225 min.

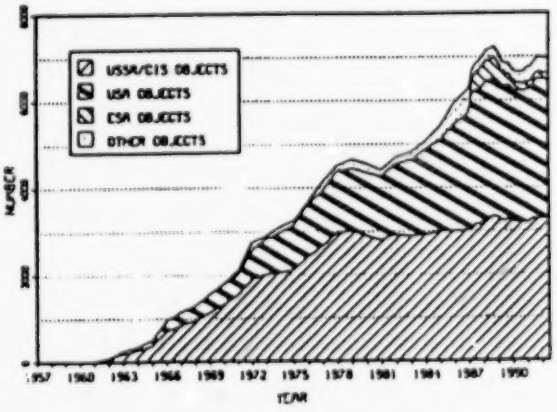

Figure 2. Cataloged objects in orbit: Cataloged objects are considered to be objects larger than 10-50 cm diameter for LEO and 1 m diameter in higher orbits.

*This document has been reproduced as it was submitted.

exclusively. These are natural particles ranging in size typically from a fraction of a micron to millimeters. These objects are in heliocentric posigrade orbits and as the Earth passes through them in its orbit around the sun, they are seen as "shooting stars" in the night sky. In the region of the outer planets, some retrograde orbit meteroids are encountered. Their presence varies with the time of year as the Earth revolves around the sun. Such meteoroids are traveling at very high speeds, on average two and a half times the velocity of objects in LEO, and the material of these objects is quite similar to grains of sand. On the other hand, debris from man-made activities are of larger size, of much more dense materials and continuously orbit the Earth.

Discussion and evaluation of the consequences of objects which have escaped Earth orbit or have returned to Earth through uncontrolled reentry, while meriting attention as a separate issue, are not further discussed here with the exception of one point: All reasonable effort should be made to avoid the accidental uncontrolled reentry of large objects, which could partially survive entry heating and pose a potential hazard to people and property on ground.[1]

Likewise, the special hazards of selected Earth-orbiting satellites carrying radioactive materials, are also reserved for later considerations.

The natural meteoroid environment, which is successfully countered with established spacecraft design features, is employed as a reference by which the orbital debris hazard can be placed into proper perspective. Orbital debris markedly exceeds the meteoroid population for objects larger than 1 mm and as a result is now considered the primary particulate design environment for manned and unmanned space systems.

An important factor to consider is that there is no net benefit if only one of the presently active spacefaring nations introduces preventive measures. Space is a "commons" used by many for their individual and collective benefit. If it is to be protected so that all can continue to exploit its unique attributes, there must be concerted and cooperative action among the spacefaring nations. In part, this is necessary to make economic competition equitable, but it is also necessary to keep valuable operational regions technically and economically viable for the future.

Since operational lifetimes are generally much shorter than the orbital lifetime of both LEO and GEO satellites, it becomes clear that some active control of these regions of space must be required. Unfortunately, because these have been the most widely used regions of space, they also have the largest population of orbiting objects. In LEO, both inadvertent and deliberate explosions have added significantly to this spatial population. To minimize collisions among objects large enough to generate substantial further debris, some active control may be required.

The purpose of this position paper is to convey clearly the urgency of taking action to control the growing orbital debris population and to make recommendations for possible methods to initiate selected control options. Efforts to increase awareness of orbital debris and to develop methods for debris mitigation have gained momentum

Categories of Orbital Debris

Only about 6% of the cataloged objects are operational satellites. About one-sixth of the objects are derelict rocket bodies discarded after their use, while over one-fifth are non-operational payloads. Pieces of hardware released during payload deployment and operation are considered operational debris and constitute about 12% of the cataloged population. Last, the remnants of the over 100 satellites and rocket stages that have been destroyed on orbit account for over 40% of the population by number. These proportions have varied only slightly over the last 20 years.

Small-size orbital debris (size ranging from 1/1000 mm to 20 cm) include particles from paint, coating, aluminum oxide of solid motor propellant, and fragments of breakups.

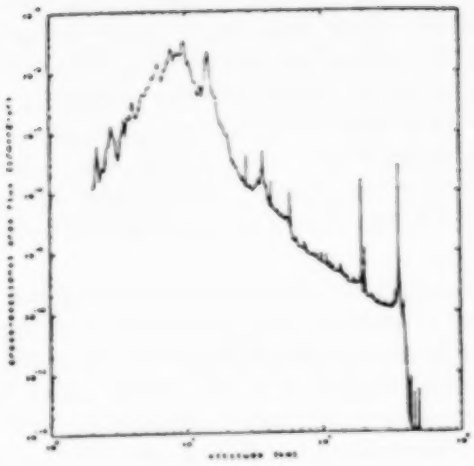

Figure 3a

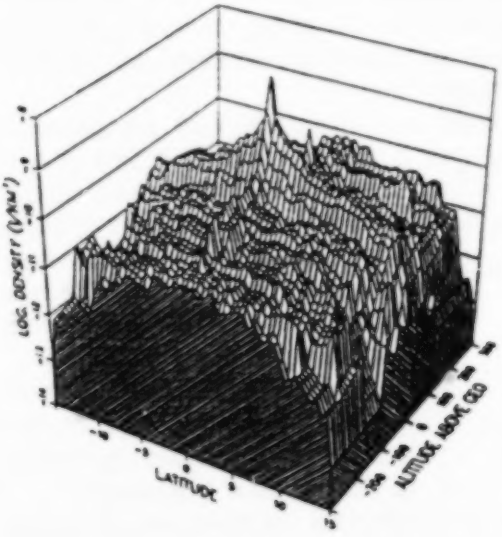

Figure 3b

Figure 3. Spatial distribution of orbital debris: Fig. 3a displays the debris flux with respect to a circular orbit. In Fig. 3b the spatial density of debris near the geostationary orbit is displayed (averaged over the geographical longitude). The maximum spatial density levels for LEO and GEO are nearly comparable. In GEO the spatial density drops off very quickly as one moves away from the geostationary belt where many satellites are controlled within a very narrow altitude band.

over the last few years, although detailed scientific uncertainties remain in a number of critical areas. The primary facts are a matter of consensus. This paper recommends certain initiatives that could be implemented immediately to mitigate and control future debris generation.

2. PRESENT STATUS

The distribution of orbital debris may be quantified by spatial density, SPD, measured in average number of objects per cubic kilometer or by flux in objects per square meter per year. Figure 3 plots the flux of tracked objects for LEO and the SPD in GEO showing that the peak values are nearly comparable in magnitude, but the collision risk in LEO is much higher than in GEO because of the higher relative velocities and the much smaller regional volume. The number of objects in LEO has doubled since 1978, while the population in GEO has more than doubled since 1982. Today about 6% of the tracked object population resides in GEO or near GEO orbits. In total, about 350 - 400 spacecraft have been inserted in the geostationary ring. Over 100 upper stages and several separated apogee boost motors (ABM)[2] are located in the geostationary ring or its vicinity.

During the space age, the cataloged population (all altitudes combined) has grown at nearly a net linear rate of 200 entries per year. The only natural removal mechanism is air-drag, whose effect decreases with altitude. (See **Atmospheric Drag Effects**.) Unfortunately, at altitudes higher than about 1000 km, it is less effective. Most objects put into these regions will stay for tens to millions of years. The consequence is a steady accumulation of mass at higher altitudes.

The major concern with orbital debris is that it might strike an operational satellite or other massive object, causing any of a wide variety of detrimental consequences. If a trackable object in LEO were to strike another trackable object in LEO (like an operational satellite) both would most likely be destroyed, due to the large relative kinetic energy available. (See **Breakup Modeling**.)

Debris in the 1 - 10 cm size range, though too small to be tracked by operational systems and to be sensed by most ground systems, are

large enough to cause catastrophic damage to many satellites. Particles of this size have been produced by the thousands from many of the 109 known spacecraft and rocket body breakups to date. The rate of breakup events has not subsided, despite the increased concern and awareness of orbital debris. (See **Breakup Modelling**). The on-orbit evolution of these centimeter-sized debris is determined by the physical characteristics of the fragments, initial velocity distribution, and various perturbing forces. At altitudes where atmospheric drag is less pronounced, the population of these types of objects may be much larger than the trackable population, possibly by factors as large as two to ten.[3] At altitudes below 500 km, these smaller objects may be less populous than the trackable population because the lower mass to area ratio makes them more susceptible to atmospheric drag. The trackable population is growing at a faster rate at higher altitudes than lower altitudes, due partially to the reduced influence of atmospheric drag.

Orbital debris in the 1 mm - 1 cm size range may produce mission-degrading effects on spacecraft which they encounter. These objects are thought to be more numerous than larger ones in orbit even though there have been few, if any, actual measurements of impacts by fragments of this size. Characteristic ballistic coefficients of these small debris and the influence of non-gravitational effects (e.g., solar pressure) may, however, lead to more rapid orbital decay.

On the other hand, numerous measurements of impacts by fragments smaller than 500 microns have been recorded on surfaces exposed to the space environment. A recent analysis has identified more than 50 impact features on the U.S. Shuttle orbiter windows over 40 missions (up to May 91), leading to the replacement of nearly 25 panes of them. Preliminary analysis has shown, that up to 75% of the windows replaced were pitted by man-made debris. Thousands of such impacts are being examined on space-exposed surfaces of NASA's LDEF (Long Duration Exposure Facility). About 15 - 50% of these were the result of man-made particulates depending on the orientation and composition of the surface.

In general, the impact flux increases as fragment size decreases. Figure 4 shows a composite of flux

Atmospheric Drag Effects

The Earth's atmosphere produces drag forces that retard an orbiting object's motion and cause it to spiral into denser regions of the atmosphere where it typically burns up due to air friction effects. The less "massive" the object for a given cross-sectional area, the greater its drag will be, resulting in a shorter lifetime in orbit. The atmospheric density at a given altitude increases with solar flux, which has an 11-year cycle. This accounts for the periodic "cleansing" effect which reduces the orbital population during high solar cycle periods.

Apart from a few exceptions (luni-solar perturbations of highly eccentric orbits and solar radiation pressure for high area-to-mass ratio objects), air-drag is the only natural mechanism removing objects from orbit. At higher altitude this mechanism becomes less efficient (see Table 1), and objects will in general remain for extended periods in orbit. Therefore, at higher altitude a steady accumulation of man-made objects takes place.

TABLE 1. Lifetime of circular orbits: For an average-type satellite the lifetime for several circular orbits is shown.

Orbit altitude (km)	Lifetime
200	1-4 days
600	25-30 yrs
1000	2000 yrs
2000	20000 yrs

Breakup Modeling

There is a wide variety of causes for satellite breakups: battery failure, deliberate detonation, overpressurization and/or ignition of fuels, accidental collision, and weapons testing. The severity of a fragmentation event is largely a function of two parameters: the available energy for breakup and the efficiency by which the energy is coupled to the satellite. When a rocket body explodes due to overpressurization of propellants, there is a moderate amount of energy which couples well with the structure until a rupture occurs and the gases are allowed to vent instead of stressing the tank. As such, there is a moderate amount of energy transfer to the structure. Deliberate detonations can be designed to couple as much or as little of the energy to the structure as desired. Battery malfunctions routinely involve small to moderate amounts of energy which do not normally couple with the entire structure very well.

Another class of breakup is the collision-induced event. The available kinetic energy (KE) for the encounter, as seen by the satellite, is a function of the impactor mass (M_i) and the relative velocity between the impactor and satellite (V_{IS}):

$$KE = \frac{1}{2} M_i V_S^2$$

In LEO the average relative velocity between any two orbiting objects is about 10 km/s. At this speed, an 80 gram object (about 5-10 cm in size) introduces the KE equivalent to 1 kg of TNT. The efficiency at which this KE is absorbed by the impacted satellite is a function of its structure. For a "typical" LEO satellite of mass 500 kg, a 1 kg object would probably completely destroy it upon impact. Even a 1 cm fragment has sufficient energy to significantly disrupt any satellite's operations.

measurements for surfaces that were exposed mainly in the 400 - 600 km altitude region and the flux predicted from the USSPACECOM catalog data over the 500 - 1100 km range. Similar comprehensive in situ data collection efforts at higher altitudes have not yet been undertaken.

The risk to operational assets in orbit varies by altitude, inclination, spacecraft characteristics, and year. (See **Probability of Collision.**) There are an infinite number of possible combinations, but two specific situations might be illustrative. First, for a 20-square meter cross section satellite at 850 km, the probability of a collision with a trackable object is 1:10,000 per year. An operational satellite in this region will have a 99.9% probability of surviving a 10-year mission without being struck by a cataloged object.

The probability that any two trackable objects will collide (collision rate) in this altitude region, 800 - 1000 km, during one year is 1:100. At this level of hazard it is likely (greater than 50% chance) that a collision-induced breakup of a trackable object by another trackable object will occur in the next 10 to 15 years.

It has been estimated that there are 2 to 10 times as many 1 - 10 cm orbital debris fragments in LEO as there are trackable objects. Assuming that this ratio has been at least five since the mid-1970s, there is a 40 - 70% chance that one of the breakups in the 800 - 1000 km altitude band was caused by the impact of a piece of orbital debris in the 1 - 10 cm size range.

The second orbital case considered is that of a particular 50-square meter controlled spacecraft in GEO. (See **The Geostationary Orbit and End-of-Life Disposition.**) It has a 1:1,000,000 chance per year of being struck by an uncontrolled and trackable object. The collision rate among all trackable objects will only be approximately 1:500 per year. Due to the inability to sense objects smaller than one square meter, the hazard from objects greater than 10 cm in size for GEO may be underestimated at this time.

In GEO, we basically have three different collision risks for operational spacecraft. First, a piece of debris may collide with an operational station-kept spacecraft, as stated above. Second, operational spacecraft located within

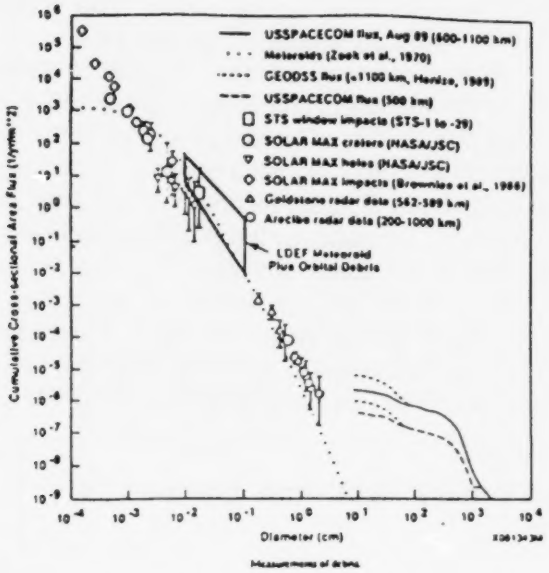
USSPACECOM flux, Aug 89 (600-1100 km)
Meteroids (Zook et al., 1979)
GEODSS flux (=1100 km, Hardin, 1989)
USSPACECOM flux (500 km)
STS window impacts (STS-1 to -29)
SOLAR MAX craters (NASA/JSC)
SOLAR MAX holes (NASA/JSC)
SOLAR MAX impacts (Brownlee et al., 1988)
Goldstone radar data (562-589 km)
Arecibo radar data (200-1000 km)
LDEF Meteroid Plus Orbital Debris
Cumulative Cross-sectional Area Flux (1/sq m*2)
Diameter (cm)

Figure 4. Particulate flux as function of size: A plot of impact flux as a function of impactor size has been formulated by combining measurements taken by a variety of methods over many years and a range of altitudes.

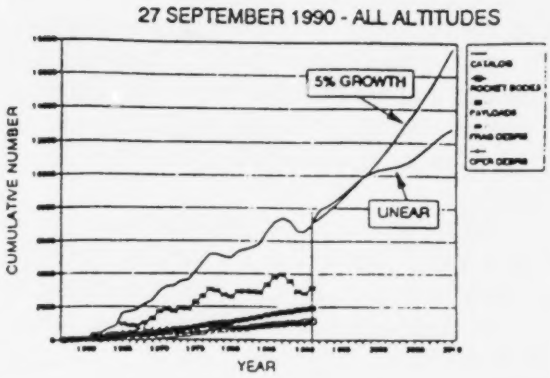

Figure 5. Growth of cataloged population: The growth of the cataloged Earth orbit population has been nearly linear with major changes caused by breakup events and solar activity cycles.

the same longitude window (collocated spacecraft) could collide with each other. The heavy use of the geostationary orbit makes it necessary to place several active spacecraft in the same longitude window of typically 0.2 degree (=collocation). The chance of a close approach of 50 m (measured center to center) in the second scenario for a four-spacecraft cluster in a typical longitude box is about 60% per year, assuming that the spacecraft are operated independently by different control centers. In most cases, however, collocated spacecraft are operated by the same control center, thus reducing the probability of collision.

Probability of Collision

The probability that two items will collide in orbit (PC) is a function of the spatial density of orbiting objects in a region (SPD), the average relative velocity between objects in that region (VR), the collision cross section of the scenario being considered (XC) and the time the object at risk is in the given region (T):

$$PC = 1 - \exp(-VR \times SPD \times XC \times T) \approx VR \times SPD \times XC \times T$$

The relationship is derived from the kinetic theory of gases by assuming that the motion of objects in the region being considered is random. For a moderate-sized satellite ($XC = 10\ m^2$) in an 800 km circular orbit, the PC is about 1/100,000 per year. Note that the PC equation may be approximated by the product of the four terms as long as the value is very small (less than 1/10,000). As the cataloged population, lifetime, and satellite size increase, the PC will also increase.

A third potential collision risk in GEO is connected with station-acquisition maneuvers (reaching the nominal longitude after launch) and the relocation of geostationary satellites. This third type of collision risk is between two satellites that are not collocated. Relocation is achieved through a neighboring transfer orbit, either a few km above or below the geostationary orbit.

The present hazard to satellites in orbit from debris varies depending on altitude, mission, satellite construction, etc. Manned missions require shielding due to reliability and safety considerations. Sensitive parts of satellites may also need protection. The Radarsat spacecraft of the Canadian Space Agency became the first unmanned satellite to incorporate shielding to counter the projected debris collision hazard. The complexities of determining whether a satellite is at risk is very mission and user dependent.

The most distressing aspect of the orbital debris problem is that it is getting worse in those regions most intensely used and could grow out of control at some altitudes and inclinations within the next few decades. The uncertainty involved in many of the present analyses highlights the need for technological developments to more accurately depict the hazard from orbital debris, prevent its creation, and provide protection from its impact. (Appendix C describes technology issues in more detail).

3. NEED FOR ACTION

The cataloged population is an important observable parameter for the prediction of the future state of the orbital environment. Figure 5 plots the growth of the trackable orbital debris population from 1960 to present with two extrapolations for the future. The lower of the two curves represents the continuation of the historical 200/year growth modulated by solar activity cycles. The upper curve depicts an annual 5% growth rate.

The evolution of the orbital debris environment cannot precisely be predicted due to the possibilities of increased launch rates by a growing number of space powers, especially in light of new smallsat technology, but may be tempered somewhat by the possible decline in former Soviet space activity. The two future growth curves (Fig. 5), however, do provide reasonable bounds for at least the next decade. It is of some interest to note that while the U.S. launch rate has declined from 215 (1960-61) to

The Geostationary Orbit and End-of-Life Disposition

The ideal geostationary orbit has a radius of 42,164 km and lies in the equatorial plane. The direction of motion is in the same sense as the rotation of the Earth. A satellite in this orbit would complete an orbital revolution after one sidereal day or approximately 23h 56m 4s.

Due to orbital perturbations caused mainly by the ellipticity of the Earth at its equator and gravitational attraction by Sun and Moon, orbit adjustments are necessary which involve the use of onboard thrusters and expenditure of propellant. Once all the propellant is consumed, or if the spacecraft is no longer controllable, the spacecraft will begin its free motion. The inclination will cyclically vary over a period of about 53 years and reach a maximum of about 15°. It will typically traverse the geostationary orbit in North-South direction twice every day, reaching a maximum relative velocity with respect to controlled satellites of about 800 m/s, which is about three times faster than a jet transport. Its longitudinal position will no longer be kept constant.

In order to eliminate the risk of controlled spacecraft colliding with an abandoned spacecraft, geostationary satellites should be reorbited to a disposal orbit at end-of-life. Reorbiting into a disposal orbit should be established with a series of at least three burns in order to preclude deposit in a less desirable orbit due to unanticipated fuel depletion. The velocity requirement for reorbiting is 3.63 m/s, or equivalent to about a month's stationkeeping budget, for every 100 km altitude increase.

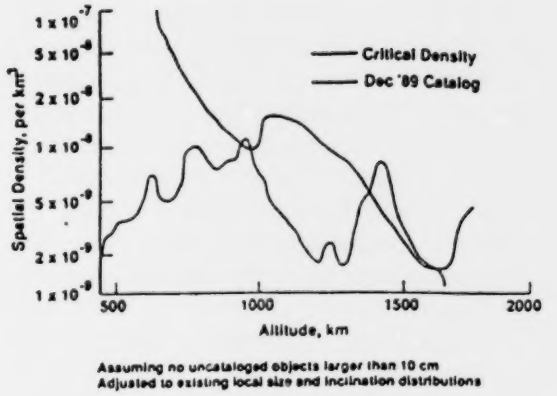
Critical Density
Dec '89 Catalog
Spatial Density, per km³
Altitude, km
Assuming no uncataloged objects larger than 10 cm
Adjusted to existing local size and inclination distributions

Figure 6. The critical density: Some scientists suspect that certain regions of Earth orbit have already reached the "critical density," which may lead to an increased growth in the on-orbit population due to collision-induced breakups.

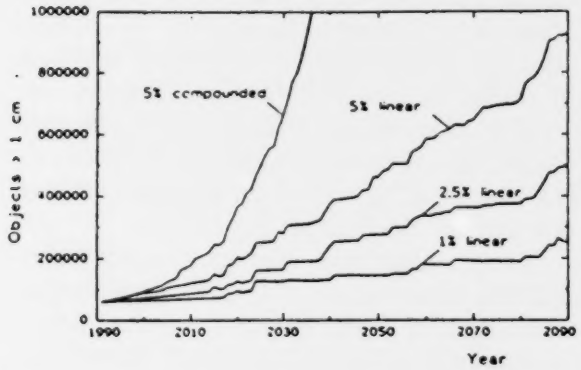

Figure 7. Long-term evolution of all objects >1 cm due to collisional cascading effects.

Parameter: increase of basic population (launches and explosion debris, without collision fragments);
Linear: percentage with respect to year 1990;
Compounded: percentage with respect to the preceding year.

102 (1980-81), the mass delivered to orbit is constant.

Several studies have been conducted that discuss the possibility of a cascading effect occurring in LEO where the rate at which debris is produced by collisional encounters creates debris more quickly than it can be cleansed via atmospheric drag. (See **Atmospheric Drag Effects.**) This phenomenon could then cause an increase in the growth rate of orbital debris, resulting in much greater collision hazard for nearby satellites. This population density (called the critical density) may have already been attained at several altitudes as shown in Figure 6.

Much more research is needed to determine if this methodology is an accurate and appropriate measure of merit. Other analyses have stated that the population in LEO need only double for the onset of a runaway growth to take effect. From Figure 5 it can be seen that this might occur in the next 10 to 15 years, if there are no changes to the way operations are conducted in space. When, or if, this situation is reached, the population will grow exponentially (Fig. 7). Space operations in some altitudes will then be severely hampered.

Previous studies assumed satellite populations fairly evenly spread across hundreds of kilometers, but the advent of constellation architectures, such as Iridium and Brilliant Pebbles, may add another dimension to this analysis. Multisatellite constellations clustered in narrow altitude bands may be much more sensitive to population densities leading to collisional breakups. The individual satellite system designers should pay careful attention not only to how they deploy and operate their own systems, but also to the actions of users in neighboring space regions.

It should be noted that calculations for probability of collision use average spatial density values for a given altitude. It is possible, however, that satellites may encounter regions of elevated spatial density, especially soon after a breakup event before the cloud disperses significantly.

4. DEBRIS CONTROL OPTIONS

The need to change the manner in which space missions (launch, deployment, operations, and termination) are conducted has been debated at length. All investigations addressing the long-term evolution of orbital debris conclude that, without changes to the way space missions

are performed, regions of near Earth space will become so cluttered by debris that routine operations will not be possible. The options available to decrease the growth of orbital debris depend greatly on the altitude of the mission, design of the hardware, and the commitment of the international spacefaring community.

The amount of debris can be controlled in one of two ways: debris prevention or debris removal.[4] Table 2 shows individual techniques under each of these categories.

TABLE 2. Methods to reduce debris population.

PREVENTION	REMOVAL
Design and operations	Retrieval
Expulsion of residual propellants and pressurants	Propulsive maneuvers (deorbit)
Battery safety (vent or fuse)	Drag augmentation
Retention of covers and separation devices	Solar sail
Propulsive maneuvers (reorbit)	Tether Sweeping Laser

Several of these techniques are already practiced by space users at this time. The fact that some debris minimization techniques are already being used voluntarily bodes well for the future, but it is not clear at this time which of the methods are most effective and how to measure the cost-benefit tradeoffs for each. Continued research is required in this area. Identification of realistic and effective methods is the most important issue.

Some prevention methods already in limited use include application of debris catchers for explosive bolts, fewer releasable parts, and multiple payloads on a single launch. These have been incorporated on several launch vehicles to date.

Debris removal options have been used on a few occasions to date, e.g., retrieval via the U.S. Space Shuttle or deorbit. Debris removal has been used in the Soviet manned program through the deorbiting of Progress supply vehicles and space stations into oceanic areas, except Kosmos 557, Salyut 2, and Salyut 7/ Kosmos 1686.

An important category of debris prevention methods is safing of hardware to avoid breakup by explosion. The retrieval of large derelict objects may be expensive and difficult, but it is certainly more difficult and expensive to recover the debris created from the fragmentation of such an object. For LEO rocket bodies, the expulsion of propellants and pressurants has been used successfully in the past and provides a significant measure of safety for the future. Several rocket vehicles already routinely perform these expulsion procedures for hardware in sun-synchronous orbits (Ariane, Delta and Long-March) to reduce the chances of future fragmentation events. From flight V60 onward all Ariane upper stages will be vented, irrespective of the type of orbit. The Delta second stage is burned to depletion after deployment of the payload and execution of a maneuver to avoid a collision. The Japanese H-1 second stage (LE-5) has vented main-engine residual propellants and gas-jet propellant after completion of payload separation. This action was conducted irrespective of mission and was not limited to sun-synchronous missions. A similar procedure is planned for the H-2 launch vehicle. The Chinese Academy of Sciences is also investigating similar procedures for the Long-March upper stage.

Unfortunately, fuel venting has not been applied to the more than 100 liquid upper stages in the vicinity of the geostationary orbit. Such a procedure should be initiated as soon as practical and include the liquid altitude and trim systems of solid rocket boost-stages.

On several previous occasions, the overcharging of a battery on a satellite has caused small breakup events, and precautions should be taken to prevent this type of occurence in the future.

Another important category of preventive action is reorbiting into a disposal orbit. For example, GEO satellites at end-of-life may be boosted as high as several hundred kilometers above GEO to prevent continual interaction with other objects in the GEO belt. The re-orbiting move is presently the only practical way to reduce the collision risk in GEO. This procedure has been performed over 60 times. Some of the maneuvers have been incomplete due to poor fuel estimation, which left defunct payloads in

slightly elliptical orbits that pass through the GEO region. Although much study is required on the use of movements to supersynchronous disposal orbits by GEO satellites, such as determination of the minimum altitude increase or improved propellant gauging, the orbit-raising move should be continued. A minimum orbit-raising altitude of 300 - 400 km is recommended. To date the average reboost altitude has been about 250 km. A multiple-burn strategy should be adopted which takes into account uncertainties in the propellant estimate. In the long run, a more permanent disposal method must be considered.

In LEO the use of drag augmentation, propulsive maneuvers, solar pressure movement, or tether removal may require the development of hardware not presently available and may impose a performance penalty. Drag augmentation hardware might include inflatable devices that would rigidize upon deployment, presenting a much greater cross-sectional area to the atmosphere to increase the drag forces on the object. Drag augmentation will work best for low altitude missions, below 600 - 700 km, even though it would provide some lifetime reduction for altitudes as high as 1200 km. Propulsive maneuvers to force deorbit, or at least a reduction in orbital lifetime, may be immediately possible for some rocket stages but not for the majority of large derelict hardware already in orbit. As long as attitude and control capabilities are maintained on the rocket stage, a small maneuver (away from the released spacecraft to avoid contamination from rocket firings), followed by a burn, might produce the appropriate change in orbital elements. (See **Mass Penalties for Removal of Objects from Low Earth Orbit.**)

Additionally, the ability to move objects that have never had any propulsive capability, years after their use, presents a difficult problem. The inclusion of some system that remains with the object (spacecraft or rocket body) possibly for many years, then performs a maneuver, may create an operational hindrance and safety concern. The installation of some remote propulsion system at the proper time would require a significant amount of effort for rendezvous, attachment (to a possibly hazardous piece of hardware) and coordination of the maneuver. A remotely controlled "space tug" deployed to rendezvous with and deorbit large derelict objects might provide an effective means to remove debris. This concept is feasible with existing technology, but cost considerations have precluded it from use thus far.

Another method by which a derelict object may be moved is a solar sail, which would use solar radiation pressure to change its orbital elements. Drag on these sails will also assist in the removal process. This technique would require an increase in hardware costs and would create a very slow change in orbital elements, but would be equally effective across a wide range of altitudes. It should be noted, however, that the use of drag augmentation and solar pressure devices will increase the physical area, and thus the collision cross section, of the object that is being removed.

The use of a tether may assist object removal in a number of independent ways: via momentum exchange at either deployment or retrieval and electromagnetic drag. In any case, the use of a tether will require some hardware development and manufacture, plus the inherent operational reliability problems of adding other types of hardware to already complex systems. The goal in removing "residual" satellites, i.e., those which are not capable of satisfactorily performing or contributing to the support of their mission, should be to lower the probability of collision with operational systems and to eliminate further creation of debris through possible breakups.

The use of some type of sweeper mechanism has been discussed on numerous occasions. There are several types of technology efforts that must be initiated in support of this type of removal method. First, some material must be developed that will be able to withstand the impact of orbital debris, absorbing or reducing the particle's energy without releasing more debris than the sweeper has collected. Second, a passive device would sweep up anything in its path without any regard for national ownership or present operational status, so some type of control mechanism must be developed. Third, the size of a sweeper may have to be several kilometers in diameter for it to be effective, which could pose some structural construction difficulties. These considerations may make such systems impractical.

Mass Penalties for Removal of Objects from Low Earth Orbit

Due to the effect of the Earth's gravitational field, it is most economical to deorbit into the Earth's atmosphere below 25,000 km altitude and to boost to a higher altitude above that orbit. The objective in a removal maneuver is to prevent objects that are no longer functional from colliding with future functional systems.

Figures 8 and 9 illustrate the propulsive mass penalty to deorbit a rocket body from a circular orbit or elliptical geosynchronous transfer orbit.

5. METHODS OF DEBRIS CONTROL

There is a need to initiate internationally accepted debris control measures at the source to preserve useful altitudes for functioning spacecraft, but there is debate as to the timing and level of options. One good way to determine what types of techniques and designs to select is to perform a series of thorough cost-benefit tradeoff studies. Though these analyses are vitally important to ascertaining the relative merit of proposed options, this committee supports the position that there are several actions that should be initiated immediately to ensure the future viability of space travel and these will be listed at the end of this paper. The participation of spacefaring countries and their supporting aerospace industries will address the balance of costs to benefits. The loss of only a few operational spacecraft from orbital debris collisions and/or abandonment of certain altitude bands may exceed the expenditures suggested by the control options identified in this paper.

The control options to be considered fall into three categories: those requiring minimal impact on operations, those requiring changes in hardware or operations, and those requiring technology development.

5.1. Options Category I

Category I comprises those options that will have the greatest impact on population control and that require no technology development

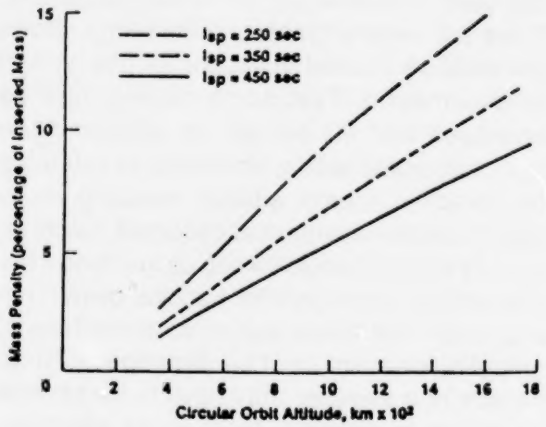

Figure 8. Mass penalty for deorbit from circular orbits: For different values of specific impulse, the mass penalty is displayed.

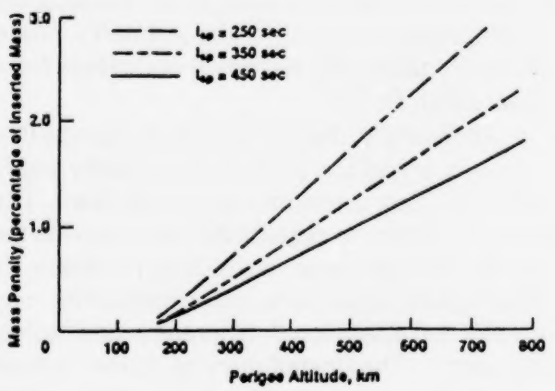

Figure 9. Mass penalty for deorbit from geostationary transfer orbit: For different values of specific impulse, the mass penalty is displayed.

and have minimal cost impacts. Some performance reduction may, however, result. These have first priority for implementation. Most have already been effected voluntarily. If a particular option requires major hardware changes for a specific space system, then for that specific system the option shall be considered category II.

(1) No deliberate breakups of spacecraft which produce debris in long-lived orbits.

(2) Minimization of mission-related debris. In many cases cost-effective engineering solutions are available with low cost for implementation. In several cases, however, the costs will no longer be minor as significant design changes will be needed (e.g., yo-yo-devices).

(3) Safing (venting) of upper stages and spacecraft in any Earth orbit.

(4) Selection of geostationary transfer orbit (GTO) parameters to minimize orbital lifetime of upper stage by keeping the GTO perigee at a low altitude, 180 - 200 km, and, possibly, by constraining the time of launch. (See **Minimization of GTO Lifetime**.) It can mean reduction of launcher performance of several percent.

(5) Reorbiting of geostationary satellites at end-of-life to disposal orbit. Minimum altitude increase 300-400 km above GEO depending on spacecraft characteristics.

(6) If separation of ABM from geostationary spacecraft is needed, then the separation should occur in a super-synchronous orbit at least 300 km above the geostationary orbit.

(7) Upper stages used to move geostationary satellites from GTO to GEO should, at a minimum, be inserted into a disposal orbit at least 300 km above the geostationary orbit and freed of residual propellant.

5.2 Options Category II

Category II comprises those options that require either changes in hardware or operational procedures. However, no new technology developments are needed. They have second priority for implementation. Category II options aim for removing used upper stages and defunct spacecraft from orbit, thus eliminating a major debris source. The options below provide candidate quantitative values.

Removal of large or compact objects which could partially survive entry heating is accomplished with a deorbiting maneuver to ensure atmospheric entry over oceanic areas during the next perigee pass.

Removal of objects which will completely burn up during atmospheric entry means to place these objects in orbits with limited lifetime, say 10 years. Hence, in these cases, natural perturbations will be exploited.

(1) Removal within 3 months of all rocket upper stages and defunct spacecraft in orbits below 2000 km mean altitude with lifetimes exceeding 10 years .

Minimization of GTO Lifetime

The GTO is a highly eccentric orbit with the perigee at low altitude (180 - 500 km) and the apogee near the geostationary orbit. Characteristic for these orbits is a long periodic change in the altitude of the perigee caused by gravitational perturbations of the Earth, Sun and Moon. The orientation of the orbit in space with respect to Sun and Moon determines whether the perigee altitude will increase or decrease. The desired effect is an initial decrease of the perigee altitude, leading to increased air-drag perturbations, and ultimately to orbit decay. The launch time of a geostationary satellite may be constrained by other factors (thermal aspects, attitude sensors, eclipse time) related to the spacecraft design, which can be in conflict with minimum GTO lifetime.

However, through appropriate choice of the initial perigee altitude (180 - 200 km), lifetime in GTO can be significantly reduced. For some launchers the performance may be significantly reduced.

(2) Removal of all rocket upper stages in GTOs and other highly elliptical orbits within 10 years.

(3) Reorbiting of upper stages and satellites at end-of-life into a disposal orbit (as a temporary measure) for circular orbits above 2000 km altitude.

5.3 Options Category III

Debris control options of category III require new developments and, in general, suitability of the method (technical feasibility, cost-efficiency) must be demonstrated. They have third priority for implementation.

(1) Removal with an orbiting maneuvering vehicle requires straightforward engineering but has not proven cost-effective at this time.

(2) Removal of objects with drag devices will require investigations into their efficiency and suitability. Despite the shorter lifetime the collision probability remains unchanged. The procedure will be most effective for altitudes below 1000 km.

(3) Removal with tethers is an interesting concept which needs further engineering feasibility studies. Grappling of the debris object (e.g., tumbling object with significant rotational energy) and attitude control are two problem areas which must be addressed.

(4) Destruction by laser may be useful but it must be performed so that the debris object is totally evaporated, otherwise additional objects are created.

(5) Debris catcher/sweeper may be feasible if discrimination or avoidance between debris and useful spacecraft can be realized.

5.4 Approaches to Implementation

Essentially, there are two approaches to implementing debris control measures: technical and legal. The technical approach contemplates discussions within national and international engineering communities leading to recommendations of certain standards of conduct. Such standards may refer to spacecraft design or operational procedures. Institutional frameworks supporting these technical discussions may range from non-governmental organizations (such as IAA and other international groups or national technical and professional groups) to international or national working groups established by national or international space agencies.

The legal approach contemplates the use of legal instruments (including treaties, resolutions, laws, regulations, executive orders, etc.) to adopt and enforce certain standards of conduct. Legal instruments may codify standards already recommended by the engineering community or may rely on other technical guidance. It is only through some legal process, national or international, that a standard can become binding on a particular State or space operating entity. Not all legal instruments are binding, such as resolutions or recommendations.

Given the complexity of the debris problem, it is particularly important that the legal action be preceded by discussions in and recommendations by national and international engineering communities. Legal action would be premature without a thorough understanding of the many facets of the debris problem.

For implementation of the control options, the committee suggests three avenues of approach. The professional and learned societies, for example Committee for Space Research (COSPAR), International Academy of Astronautics (IAA), International Astronautical Federation (IAF), and International Institute for Space Law (IISL), have an important role of education, facilitating exchange of opinion and establishing common understanding of the issue on a worldwide scale. However, since orbital debris, and more generally space debris, touch policy aspects of States (economical aspects, safety, national security) eventually international space law will be needed, which requires the involvement of governments.

The three avenues of approach, which could be taken consecutively or independently of each other include:

(1) bilateral and multilateral discussions and agreements on space/orbital debris between and among spacefaring nations and international space organizations, for example International Telecommunications Satellite Organization (INTELSAT), and International Marine Satellite (INMARSAT).

(2) Global working group of spacefaring nations and international space organizations.

(3) Discussion at International Consultative Committee on Radiocommunications/ International Telecommunications Union (ICCR/ ITU) and UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS) and other suitable forums leading ultimately to "Code of conduct", international standards, or space law addressing space/orbital debris.

Regular coordination meetings have taken place at the technical level among spacefaring nations for several years. From these meetings a consensus as to the nature of the issues and the need for action to control the growth of orbital debris has emerged. The community is striving to assess the effectiveness of debris control options already being used, to determine if they should be continued or if others should be developed.

The global working group should be put into place to review the tentative policies suggested by previous international discussions. As the control options used to reduce orbital debris become mature and their cost-effectiveness proven, limited agreements may be put into place. A forum such as the Consultative Committee for Space Data Systems (which coordinates data formats among the space agencies) may need to be established to coordinate multilateral agreements.

The UNCOPUOS has formulated a number of treaties and resolutions regulating space activities, but has not yet formally concerned itself with space debris. Several States have suggested that it would be appropriate for COPUOS to consider the debris issue. A discussion within the COPUOS might lead to the development of a set of principles or a treaty which codifies the practices and standards adhered to by spacefaring nations. (See also appendix D).

6. SUMMARY

The objective of this paper is threefold. First, to make clear how significant and severe the continued deposition of orbital debris into the near Earth environment is to the future use of space for all humankind. Second, to provide some clear guidelines as to how the international community might wish to proceed in order to combat this growing space environmental hazard. Third, to extend discussion of the debris issue by other international groups to exercise the techniques and dialogue necessary to begin to formulate international agreements on this topic.

The following actions are recommended for immediate application in a first phase:

(1) No deliberate breakups of spacecraft which produce debris in long-lived orbits.

(2) Minimization of mission-related debris.

(3) Safing procedures for all rocket bodies and spacecraft which remain in orbit after completion of their mission.

(4) Selection of transfer orbit parameters to insure the rapid decay of transfer stages.

(5) Reorbiting of geostationary satellites at end-of-life (minimum altitude increase 300 - 400 km).

(6) Separated ABMs used for geostationary satellites should be inserted into a disposal orbit at least 300 km above the geostationary orbit.

(7) Upper stages used to move geostationary satellites from GTO to GEO should be inserted into a disposal orbit at least 300km above the geostationary orbit and freed of residual propellant.

NOTES

1. Most reentering spacecraft and upper stages are destroyed by entry heating. In rare cases some solid pieces reach the Earth's surface (Skylab, Kosmos 954, Salyut-7/Kosmos-1686).

2. ABMs are used to insert spacecraft into the geostationary orbit. They are usually spacecraft-integrated propulsion units with solid propellant. Some spacecraft jettison them after GEO insertion to reduce inertial mass; other spacecraft retain such systems.

3. Recent radar measurement from Haystack indicate that in some low-altitude bands the population of centimeter-sized objects may be about an order of magnitude larger than the cataloged population.

4. Removal means to remove from orbit.

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APPENDIX A

Review of Past Activities

The need to return derelict space hardware after it has fulfilled its primary mission was discussed even before the first satellite was launched. Despite this early, insightful observation, it has taken many years for the aerospace community to respond to the growing hazard of orbital debris. The major research and policy developments in space debris were driven largely by satellite breakup events.

The two major space treaties codified in the first 15 years of the space age did not specifically address the issue of orbital debris (Outer Space Treaty of 1967 and the Liability Convention of 1972). Space debris did not receive very much attention until the mid-1970s. The series of Delta second stage explosion events (first breakup December 1973) proved to be the

catalyst for major research activities in the area of orbital debris. The American Institute of Aeronautics and Astronautics (AIAA) position paper on space debris in 1981 was the first comprehensive public pronouncement about this growing problem. Nearly simultaneously with the issuance of this paper, NASA unveiled a 10-year plan to address key issues such as measurements, environment definition, and debris control. In 1980 the International Astronautical Federation (IAF) issued, on behalf of the United Nations Outer Space Affairs Division, a study on the efficient use of the geostationary orbit where the debris management in the geostationary orbit was addressed.

The early 1980s were marked by a series of major debris-generating events in orbit and a flurry of activity by the scientific community. A NASA-sponsored workshop in the United States (U.S.) and the issuance of several minor U.S. Government (USG) reports provided the background for the significant decision to implement the policy of venting the residual propellant on board spent Delta second stages to reduce the risk of further fragmentation events involving this hardware.

In 1986 the USG established the Interagency Group (IG-Space) for the purpose of comprehensive study on space debris. In 1988 the U.S. National Space Policy on orbital debris was issued, which reads:

"All space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments, and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness. The United States government will encourage other spacefaring nations to adopt policies and practices aimed to debris minimization."

In 1985, the European Space Agency (ESA) held a workshop on the reentry of space debris. Recognizing that space debris was a general long-term problem, ESA installed a working group in 1986 which, in 1988, published ESA's Space Debris Report. ESA's Council approved a resolution on activities on Space Debris in 1989. The policy was implemented of moving spacecraft near their end-of-life out of the geosynchronous region and venting the Ariane upper stage.[1] In 1988 ESA issued requirements for prevention of debris creation.

Both studies, the ESA report and the U.S.IG-Space report (1988), came to similar conclusions and highlighted the overwhelming need to address the issue of orbital debris immediately.

During the late 1980s and the early 1990s, the activities concerning orbital debris research increased significantly. Just as the Delta breakups and the 1981 AIAA position paper had heralded in the first phase of orbital debris research efforts, the reports by the U.S. and ESA ushered in a new era of many new participants and an appreciation for the need to control space debris.

The openness of the newly formed Commonwealth of Independent States (formerly the Soviet Union) has led to a number of significant revelations, such as the first geostationary breakup as early as 1978 and the fact that the breakup of Kosmos 1275 in 1981 was probably collision-induced.[2]

In Japan, the Space Debris Study Group was founded in 1990 by the Japanese Society for Aeronautical and Space Sciences. An interim report was issued in May 1992 identifying important research areas to be pursued at a national level. These findings were based on a clear understanding that orbital debris is an issue that all spacefaring nations must cope with.

Now, as the realities of the orbital debris problem start to become clear, it is evident that the most challenging task might well be how to develop regulations, accepted practices, or treaties that serve to control the growth of this hazard. Nearly 800 papers, articles, newsletters, and books have been written on this topic, but not one binding agreement has been reached on how to mitigate and minimize orbital debris. For this reason, we believe that the most important documents to be written concerning space debris do not yet exist.

NOTES

1. Venting of the Ariane upper stage was initially only carried out for sun-synchronous orbits. From V60 onward, venting will be implemented for all flights.

2. See *Orbital Debris Monitor*, Vol. 5(2), April 1992.

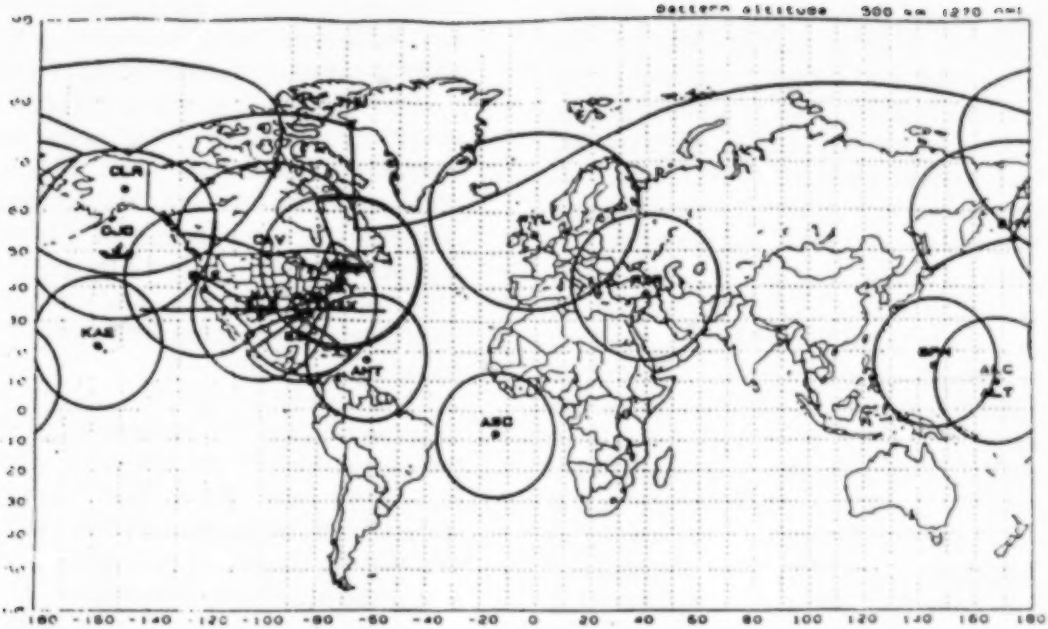

Figure B1. US radar sensor locations: The coverage areas for 500 km altitude are shown.

APPENDIX B

Space Surveillance

United States Space Command (USSpaceCom) Space Surveillance Network (SSN) began tracking satellites via telemetry during the International Geophysical Year (IGY) 1957-58. Later, skin-tracking of satellites was developed through the Naval Space Surveillance System (NAVSPASUR), which utilized radar interferometer not dependent upon spacecraft beacon. NAVSPASUR is the oldest contributor to the SSN, which now consists of radar and electro-optical sensors around the world (Figs. B1 and B2).

The capabilities of the sensors as function of altitude are illustrated in Fig. B3. At low altitude most objects smaller than 10 cm in size remain undetected since the radar cross section is too small. At the geostationary orbit the limiting size is 1 m.

By COSPAR agreement, as part of the IGY establishment of world data centers, the Northern American Air (later Aerospace) Defense Command was granted the authority to catalog satellites launched by all nations and assign them international designations known as COSPAR numbers.

Once cataloged, USSpacecom maintains the orbital elements of each object. Updates to the orbit data are needed from every few hours to every few weeks depending on whether the satellite has maneuvered, the type of orbit the satellite follows, and the level of solar activity. Sensors from the SSN electronically transmit observations on a satellite to the central computing facility in Colorado Springs. There the estimates of orbital elements are updated and the new elements distributed through NASA. As of June 11, 1992, the total number of cataloged objects in orbit was 6987. This number includes, however, 136 objects in heliocentric orbits and about 80 objects which have already decayed.

The strength of the reflected signal received by SSN radar sites also allows for estimates of the size of space objects. These size estimates

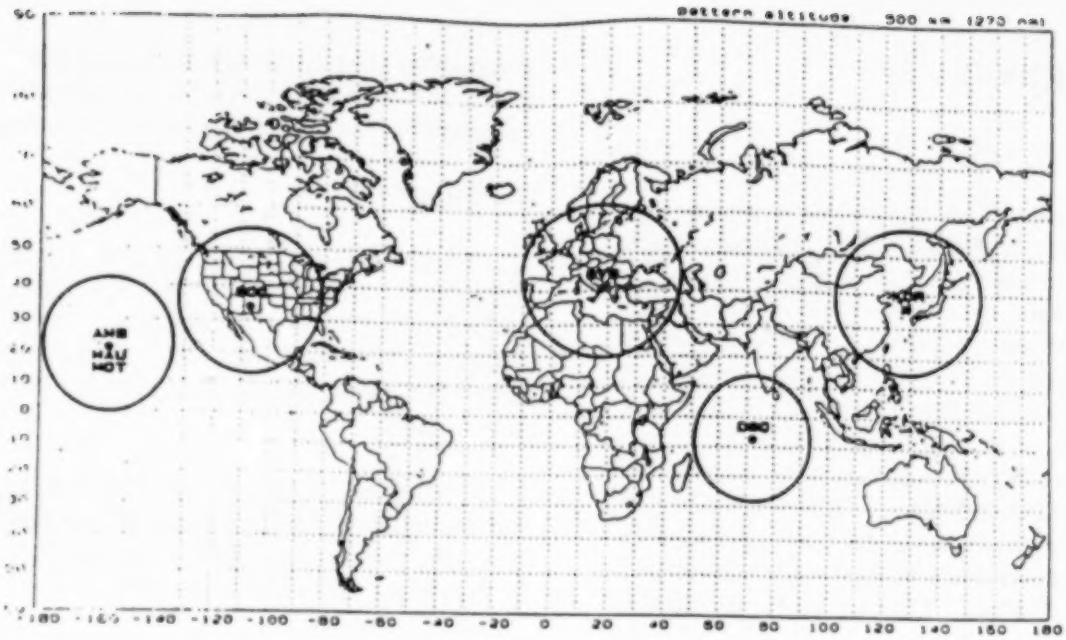

Figure B2. US electro-optical sensors: The coverage areas for 500 km altitude are shown.

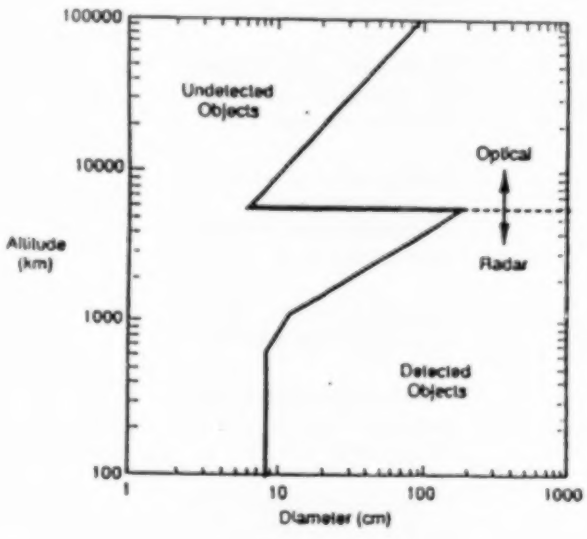

Figure B3. US Space Command sensor altitude limitation: The operational system capability to detect objects depends strongly on the altitude.

are strongly affected not only by satellite size but also by satellite configuration, satellite stability and orientation, pass geometry with respect to the radar, radar frequency, and other factors.

A similar effort in space surveillance was carried out by the former Soviet Union and is continued by Russia. Due to the geographical location of the tracking sensors and other factors, the Russian catalog comprises some 5000 objects only.

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APPENDIX C

Technology Issues

Currently, the community's ability and motivation to actively pursue all possible courses of action to control orbital debris is tempered by uncertainties in several critical areas. Even though there are presently a variety of methods and techniques in use to minimize creation of orbital debris, future expansion of such activities must be supported by efforts in better characterizing the environment and space vehicle/mission design. Tables C1 and C2 outline candidate areas for continued work in environment characterization and space vehicle/mission design. These figures provide a perspective on uncertainties that are important to reduce, but do not represent a comprehensive list of ongoing or proposed research activities.

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TABLE C1. Technology issues related to environment characterization can be addressed only through a broad range of activities including analyses, experimentation, and computer modeling.

TOPIC	UNCERTAINTY	POSSIBLE EFFORTS
Advanced Detection Methods	Debris population below 10 cm in size	Ground-based and space-based radar, optical and lidar measurements (Ref. 1)
Radar Cross-Section Modeling	Accuracy of size estimation from radar and optical measurements	Theoretical studies coupled with a laboratory and in situ measurement program
Debris Monitoring and Management System	Debris population characterization for all sizes	Develop single database dedicated to debris analysis which includes all pertinent information (Ref. 2)
Determination of Breakup Causes	Cause for fragmentation of over 25 objects	Analysis, modeling, and international investigations
Breakup Modeling	Amount and type of debris produced from fragmentation events	Theoretical studies, computer modeling, and experimental test program (Ref. 3)
Debris Cloud Evolution Modeling	Dispersion of debris from a fragmentation event	Theoretical studies, comparative analyses (theory to observation), and computer modeling (Ref. 4 & 5)
Lifetime of Small Debris	Orbital persistence of nontrackable debris fragments	Theoretical studies, computer modeling, and on-orbit experiments (Ref. 5)
Traffic Models	Future launch rates and profiles	Analytic studies and international investigations (Ref. 6)

TABLE C2. Space vehicle and mission design research should emphasize ways to reduce the generation of debris during all phases of space operations.

TOPIC	UNCERTAINTY	POSSIBLE EFFORTS
Safing of On-Orbit Vehicles	Cost and technical tradeoffs of implementing safing procedures	Theoretical studies, engineering analyses, and testing
Design for Litter-Free Systems	Cost and technical tradeoffs of incorporating debris-minimizing systems	Theoretical studies, engineering analyses, and testing
Earth Reentry Disposal	Cost and technical tradeoffs of performing reentry maneuvers	Design of new systems or modification of existing systems
Disposal Orbit for GEO Satellites	Cost and technical tradeoffs of moving GEO satellites to a disposal orbit at end-of-life. Uncertainty of propellant estimate at end-of-life.	Engineering analyses, computer modeling, economic studies, and international investigations (Ref. 7)
Shielding	Cost and technical tradeoffs of shielding spacecraft to improve reliability	Theoretical studies, engineering analyses, and experimental testing
Active Collision Avoidance	Cost and technical tradeoffs of implementing an active collision avoidance system	Engineering analyses and experimental testing

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APPENDIX D

International Policy Issues (Regulations and Space Law)

Any rule or regulation of space activities has to have a very wide international recognition, much wider than the current membership of the club of launching countries. The only existing forum with sufficiently broad participation which has a tradition in dealing with space law is the United Nations and its system of organizations. The UN, specifically the UNCOPUOS, elaborated

several international treaties adhered to by many states, including the launching countries. In addition, the UN specialized agency, the ITU, has adopted detailed rules dealing with radiocommunications between ground stations and space stations as part of the Radio Regulations.

Much of the current international space law exists in the form of treaties whose provisions are binding upon States Parties. For example, the five UN-promulgated space treaties[1], as well as the ITU Radio Regulations fall into this category. There is also a considerable body of nonbinding international space law, consisting of resolutions[2] and recommendations. These nonbinding legal instruments have significant moral authority and States generally abide by them. As evidenced by the present orbital debris situation, current international law does not adequately address the debris problem.

The present situation

A large amount of information on the subject has been put before UNCOPUOS and its Scientific and Technical Subcommittee and Legal Subcommittee. The first document dates back to 1980.

It was an information paper produced by the Outer Space Affairs Division of the UN Secretariat and was entitled "Mutual relations between space missions"[3]. It dealt with the probability of collisions in outer space and contained suggestions for preventive measures such as reducing the amount of debris generated and removing inactive satellites from orbit. At that time the catalog contained about 4500 space objects.

A more detailed treatment of space debris was provided in 1982 in a background paper for the conference UNISPACE 82[4]. COSPAR set up a large team of scientists to elaborate an authoritative and objective study. It dealt with, among other subjects, collision probability, planned decay of inactive satellites in low orbits, and removal of objects from the geostationary orbit into disposal orbits. It also commented on the concern of scientists over effects of space activities which are harmful to astronomical, radioastronomical and other scientific observations from the ground.

In 1988, at the invitation of COPUOS, a study on the environmental effects of space activities was prepared by the IAF and COSPAR[5]. It dealt with the origin and impact of space debris and with possible preventive measures. By that time, at the end of 1988, about 7000 trackable space objects had been cataloged.

On several occasions between 1980 and 1988 information was put before the COPUOS on the situation in the geostationary orbit, in particular on collision probability and on reorbiting of satellites into disposal orbits[6].

The ITU recognized the danger of collisions of active spacecraft with debris at the World Administrative Radio Conference on the Use of the Geostationary Orbit. During its first session, held in 1985, it urged the ICCR to prepare a report on the subject. The report[7] was very brief and reflected a reluctance in tackling the subject rather than a vigorous effort to find how a possible future accident could be avoided. The second session of the conference, held in 1988, did not address the space debris issue.

It is estimated that some 800 scientific and technical papers on space debris have been published in specialized literature, many of them presented at congresses of the IAF and COSPAR. This enormous research activity was not paralleled by significant international policy developments. During its session in 1989, the General Assembly, in one of its resolutions, considered it essential that member States pay more attention to the problem of collisions with space debris and called for continuation of national research in this direction. There was little progress in 1990. The Scientific and Technical Subcommittee reiterated the call but, in spite of the efforts of some States, still did not include the item on its agenda. The same reluctance was manifest in the 1990 meeting of the COPUOS[8].

At the 1991 meeting of the Subcommittee, again several States proposed to put the question of space debris on its agenda, but the necessary consensus was not reached. The June 1991 meeting of the COPUOS again heard several proposals for starting discussions on debris, but unanimity was not reached.

One positive result was attained at the 1991 COPUOS meeting after much effort of several

delegations. A consensus was reached on a paragraph in the report inviting delegations to present the results of their national research to the Scientific and Technical Subcommittee in 1992. Space debris was discussed at the 1992 session of the Subcommittee in the general debate, but not as a separate agenda item.

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